SSI Analysis of Framed Structures Supported on Pile Foundations : A Review

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Abstract

The post earthquake study of the structures reveals that the interaction of soil and foundation plays a major role in the damage/response of structure. In this regard a literature survey has been done on Frame structures supported on various foundations like isolated footings, mat foundations, combined footings or pile foundations. Persual of literature reveals that very few investigations were done on frame structures supported on pile foundations. So in this paper, an attempt is made to implement the prominent investigations on soil structure interaction analysis of framed structures supported on pile foundations. It also covers the analytical methods to predict lateral deflections of pile foundations alone (single and Group piles).

Keywords

Soil Structure Interaction; Framed Structures; Pile Foundations

Introduction

Most of the building frames are supported on combined footings, isolated footings, raft, pile foundations depending on the amount of load and the nature of supporting sub soil. Generally the multi storied buildings constructed on week strata at shallow depth are supported on pile foundations. The problem of interaction becomes more complex when soil, foundation and structure have to be modeled with equal rigor. The methods to solve the soil structure interaction problem can be grouped as direct approach, substructure approach.

Direct Approach

Direct approach is one in which the soil and structure are modelled together in a single step accounting for both inertial and kinematic interaction. Inertial interaction develops in structure due to own vibrations giving rise to base shear and base moment, which in turn causes displacements of the foundation relative to free field. While kinematic interaction develops due to presence of stiff foundation elements on or in soil causing foundation motion to deviate from free-field motions.

Substructure Approach

Substructure method is one in which the analysis broken down into several steps that is the principal of superposition is used to isolate the two primary causes of soil structure interaction that is inability of foundation to match the free field deformation and the effect of dynamic response of structure foundation system on the movement of supporting soil.

In the analysis and design of engineered structures in the past, it was assumed that the foundation of structure was fixed to a rigid underlying medium (Zhang et al. (1998), Celebi (2001)). In the last few decades, however, it has been recognized that Soil Structure Interaction (SSI) altered the response characteristics of a structural system because of massive and stiff nature of structure and, often, soil softness. Various studies have appeared in the literature to study the effect of SSI on dynamic response of structures such as nuclear power plants, high-rise structures and elevated highways (Maheshwari et al., 2004, Boominathan et al., 2004, Jaya et al., 2009, Wegner et al., 2009). The following section discusses the critical review on the SSI analysis of framed structures supported on pile foundations.

Framed Structures Supported on Pile Foundations

Although numerous works have been done on interaction analysis of frame structure resting on combined footings, isolated footings, etc., not much of work has been done interaction analysis of frame structure resting on pile foundations (Ingle and Chore 2007) except a few studies as described in the following section.

The work on frame structures supported on pile foundations was first started by Buragohain et al. in

1977 who evaluated the space frames resting on pile foundation by means of stiffness matrix method in order to quantify the effect of soil-structure interaction using simplified assumptions. In his study, the pile cap was considered to be rigid, with the neglection of of its stiffness. The stiffness matrix for the entire pile group was derived from the principle of superposition using the rigid body transformation. The foundation stiffness matrix was then combined with the superstructure matrix to perform the interactive analysis which was carried out in single step to assess the effect of soil structure interaction on the response of structure in terms of changes in member forces and settlements.

After that Cai et al. in 2000 developed a three-dimensional nonlinear Finite element subsystem methodology to study the seismic soil–pile–structure interaction effects (Fig. 1) in which the plasticity and work hardening of soil have been considered by using δ* version of the HiSS modelling. Based on their studies it has been concluded that with- plasticity-based soil model, the motion of the pile foundation deviated significantly from the bedrock motion and this departure from the ground motion should not be over looked in evaluating the seismic kinematic response of pile-supported structures. Also it has been observed that the output of the pile head motion revealed an interesting phenomenon that although the bedrock input is horizontal there is some vertical acceleration on the pile heads (column bases). In Cai et al. work the analysis was carried out on fixed boundary conditions and also damping in the foundation subsystem was neglected. Fixed boundary condition does not give the actual response as there will be lot of reflections coming back and soil damping also plays a major role in soil structure interaction analysis.

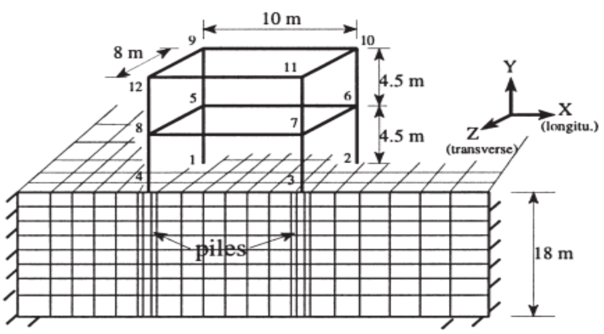


FIG. 1 EXAMPLE OF STRUCTURE AND PILE FOUNDATION DEVELOPED USING FEM BASED ON RESEARCH BY CAI ET AL. 2000

Later Yingcai in 2002 studied the seismic behavior of tall building by considering the non-linear soil-pile interaction, in which a 20-storey building is examined as a typical structure supported on a pile foundation using DYNAN computer program, leading to the conclusion that the theoretical prediction for tall buildings fixed on a rigid base without soil-structure interaction fails to represent the real seismic response, since the stiffness is overestimated and the damping is underestimated.

Besides in 2003 Lu et al., studied the dynamic soil structure interaction of a twelve storey framed structure supported on raft pile foundations using ANSYS, in which the influence of the following parameters soil property, rigidity of structure, buried depth, dynamic characteristics on SSI is studied. It has been observed that effect of SSI on displacement peak value of structure is greater with increase of structural rigidity.

Ingle and Chore (2007) reviewed the soil-structure interaction (SSI) analysis of framed structures and the problems related to pile foundations, and underscored the necessity of interactive analysis to build frames resting on pile foundations by more rational approach and realistic assumptions. It was suggested that flexible pile caps along with their stiffness should be considered and the stiffness matrix for the sub-structure should be derived by considering the effect of all piles in each group. However, the basic problem of the building frame is three dimensional in nature. Although a complex three-dimensional finite element approach, when adopted for the analysis, is quite expensive in terms of time and memory, it facilitates realistic modelling of all the parameters involved. Along these lines, Chore and Ingle (2008 a) presented a methodology for the comprehensive analysis of building frames supported by pile groups embedded in soft marine clay using the 3D finite element method (Fig. 2).

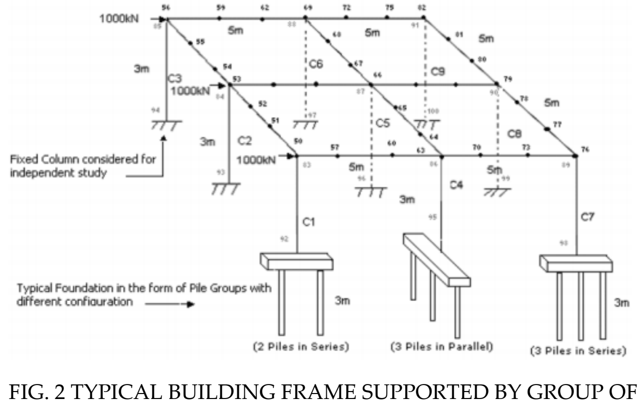


FIG. 2 TYPICAL BUILDING FRAME SUPPORTED BY GROUP OF PILES BASED ON RESEARCH BY CHORE ET AL. 2010

The effect of various foundation parameters, such as the configuration of the pile group, spacing and number of piles, and pile diameter, has been evaluated on the response of the frame. The analysis also considered the interaction between pile cap and soil. It has been concluded that with the increase in pile spacing and number of piles in a group, displacement at top of frame decreases. In addition, with the increase in diameter of piles, displacement at top of frame decreases for any spacing owing to the increased stiffness of pile group at higher diameter. Also the effect of soil structure interaction (SSI) is significant on bending moment, i.e. SSI is found to increase the maximum positive bending moment by 14.01 % and maximum negative bending moment by 27.77 %.

Chore and Ingle (2008 b) reported an interaction analysis on the space frame with pile foundations using the finite element method, wherein the foundation elements were modelled in the simplified manner as suggested by Desai et al. (1981). The pile cap was idealized as two dimensional plate elements, the piles as one dimensional beam elements, and the soil as linearly elastic independent springs. In this way, the three dimensional pile foundations can be replaced by an assembly of one dimensional beam elements, two dimensional plate elements and equivalent springs. The memory requirement is about one tenth of that required by a three dimensional modelling, making it rather easy to simulate the original complex problem.

In the studies made by Chore and Ingle (2008 a, b), an uncoupled analysis (sub-structure approach) of the system of building frame and pile foundation was presented. By this methodology, a building frame was analysed separately with the assumption of fixed column bases. Later, equivalent stiffness was derived for the foundation head and used in the interaction analysis of the frame to include the SSI effect. More recently, Chore et al. (2009) presented an interaction analysis for the building frame resting on the pile group using a coupled approach, i.e., by considering the system of building frame - pile foundation - soil as a single combined unit. Although such an analysis is computationally uneconomical, fair agreement has been observed between the results obtained using coupled and uncoupled approaches.

Chore et al. in 2010 studied the effect of soil-structure interaction on a single-storey, two-bay space frame resting on a pile group embedded in the cohesive soil (clay) with flexible cap (Fig. 2). For this purpose a three dimensional Finite Element analysis is carried out using substructure approach. A parametric study has been conducted to study the effects of pile spacing, pile configuration, and pile diameter of the pile group on the response of superstructure for different pile tip conditions. The displacement at the top of the frame is less for fixed base condition and increases by 42 to 103% when the SSI effect is incorporated. Likewise, with the increase in pile spacing, the top displacement of the frame decreases. The effect of end conditions at the pile tip is significant as well on the displacement. Though the displacements obtained for the pinned tip and fixed tip are less than those for the free tip, the end condition does not have appreciable effect for parallel configuration.

In the work of Chore et al. actual interaction with the soil and foundation has been neglected by replacing the soil with springs. Similarly, the combined effect of kinematic and inertial interaction is also neglected by the substructure analysis.

More recently Deepa et al. in 2012 did a Linear static analysis using commericial package NISA on a four bay twelve storey RCC frame structure resting on pile foundations, from which it has been observed that SSI effects increased the responses in the frame upto the characteristic depth and decerased when the frame has been treated for full depth.

Vivek et al., in 2012 presented a review on interaction behavior of structure-foundation-soil system. In which he gave a brief description of research done by various researchers on linear, nonlinear, elasto-plastic, plastic soil structure interaction effects under static and dynamic loading conditions.

As the well known reason why our structures are always safe against gravitational loads and various damages to them (structures and foundations) is mainly because of lateral motion. In the following section, the various analytical methods available for single and group piles (not the review) has been outlined by discussing the advantages of one over the other.

Pile Foundations

Pile foundations, the oldest method of construction for overcoming the difficulties of foundation on soft soils, are used to support bridges, high rise structures, offshore platforms, marine structure etc. Significant damage was caused to pile supported structures in the

past during major earthquakes such as 1906 San Francisco earthquake, 1964 Niigata and Alaska earthquakes, 1995 Kobe earthquake, 2001 Bhuj earthquake, which led to an increase in the demand to reliably predict the response of piles to ground shaking. Since then extensive research has been carried out and several analytical and numerical procedures have been developed to determine the static and dynamic response of piles subjected to horizontal or vertical loads. Meanwhile, full scale experimental observations on the pile's behaviour and numerous model testing have been carried out. In this paper an attempt is made to discuss the details of the same. The following section briefly summarizes the various analytical methods existing for single pile and group piles.

Analytical Methods for Single Piles

Single piles are mainly used for coastal structures such as mooring and berthing piles, but usually formed in groups. However, tall buildings, offshore platforms, quays, viaducts, and bridge piers are generally built on pile groups. The difference between the behaviour of single piles and pile groups is that pile group response is influenced by the nonlinear pile-soil-pile interaction, the effect of the pile cap, the spacing of piles, and the arrangement of piles with respect to the direction of applied force (Charles et al. 2001). So in order to have a good understanding on the group behaviour, first the single pile behaviour is discussed followed by group pile behaviour.

Analytical methods to predict lateral deflections, rotations and stresses in single pile can be grouped under the following four headings

1) 1).Winkler Approach
2) P-Y Method
3) Elastic Continuum Approach
4) Finite Element Method

1) Winkler Approach

The Winkler approach, also called the sub grade reaction theory, is the oldest method to predict pile deflections and bending moments. - The approach uses a series of unconnected linear springs to model the soil with stiffness, K_h, expressed in units of force per length squared (FL^{-2}). The behaviour of a single pile can be analysed using the equation of an elastic beam supported on an elastic foundation (Hetenyi 1946), which is represented by the 4^{th} order differential beam bending equation.

$$E_p\, I_p \frac{d^4 u}{d z^4} + Q \frac{d^2 u}{d z^2} = -w = -pd = -K_h u d$$

$$E_p\, I_p \frac{d^4 u}{d z^4} + Q \frac{d^2 u}{d z^2} + K_h u d = 0 \qquad (1)$$

Where E_p Pile modulus of elasticity
Q Axial load on pile
I_p Pile cross section moment of Inertia
d Pile diameter
w Soil reaction per unit length over the pile (distributed load)
p Soil pressure over the pile
K_h Soil lateral subgrade reaction modulus
u Lateral deflection of pile at point x along the length of the pile

Solutions to Eq (1) have been obtained by making assumptions simplification regarding the variation of K_h with depth. The most common assumption is that K_h is constant with depth for clays and K_h varies linearly with depth for sands. Poulos and Davis (1980) and Prakash and Sharma (1990) provided tables and charts that can be used to determine pile deflections, slopes, and moments as a function of depth and non-dimensional coefficients for a constant value of K_h with depth.

Despite its frequent use, the method is often criticized because of its theoretical shortcomings and limitations. The primary shortcomings are the modulus of sub grade reaction that is not a unique property of the soil, but depends intrinsically on pile characteristics and the magnitude of deflection; and the method is semi-empirical in nature; axial load effects are ignored and the soil model used in the technique is discontinuous. That is, the linearly elastic Winkler springs behave independently and thus displacements at a point are are free from being influenced by displacements or stresses at other points along the pile.

McClelland and Focht (1956) augmented the sub grade reaction approach using finite difference techniques to solve the beam bending equation with nonlinear load versus deflection curves to model the soil. Their approach is known as the p-y method of analysis. This method has gained popularity in recent years with the availability of powerful personal computers and commercial software such as COM624 (Wang and Reese 1993) and LPILE Plus3.0 (Reese et al., 1997). A brief summary of the p-y method of analysis is presented in the following section.

2) P-Y Method

The p-y approach to analysis of response of laterally loaded piles is essentially a modification (Horvath 1984) of the basic Winkler model, where

p is the soil pressure per unit length of pile and y is the pile deflection. The soil is represented by a series of nonlinear p-y curves that vary with depth and soil type. An example of a hypothetical p-y model is shown in Fig. 3. The method is semi-empirical in nature because the shape of the p-y curves is determined from field load tests. Reese (1977) has developed a number of empirical curves for typical soil types based on the results of field measurements on fully instrumented piles. The most widely used analytical expression for p-y curves is the cubic parabola, represented by the following equation.

$$\frac{p}{p_{ult}} = 0.5\left(\frac{y}{y_{50}}\right)^{1/3} \qquad (2)$$

where p_{ult} Ultimate soil resistance per unit length of pile

y_{50} Deflection at one - half of the ultimate soil resistance

The deflections, rotations, and bending moments in the pile are calculated by solving the beam bending equation using finite difference or finite element numerical techniques.- The pile is divided into a number of small increments and analysed using p-y curves to represent the soil resistance. In this representation, the axial load in the pile, Q, is implicitly assumed constant with depth, to simplify computations. This assumption does not adversely affect the analysis because Q has very little effect on the deflection and bending moment (Reese 1977).

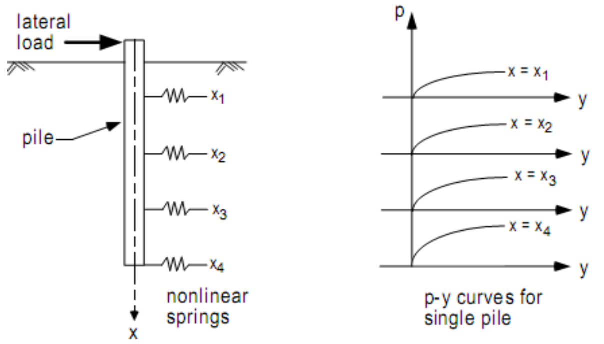
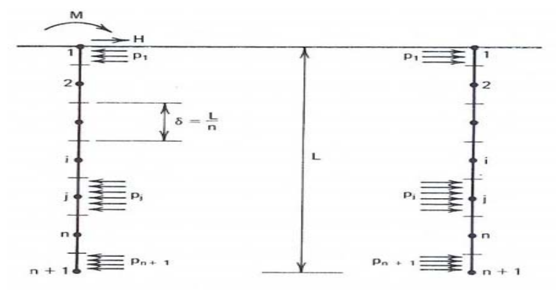


FIG. 3 p-y MODEL FOR LATERALLY LOADED PILES

The method outperforms the sub grade reaction approach because it accounts for the nonlinear behaviour of most soils without the numerical limitations inherent in the sub grade reaction approach. However, the method has some limitations; such as the p-y curves are independent of one another. Therefore, the continuous nature of soil along the length of the pile is not explicitly modelled. The acquisition of the appropriate p-y curve is similar to the gain of the appropriate value of K_h; and one must either perform full-scale instrumented lateral load tests or adapt the existing available standard curves for use in untested conditions.- These standard curves are limited to the soil types in which they are developed, but not universal.

3) Elastic Column Approach

Poulos (1971 a, b) presented the first systematic approach to analyze the behaviour of laterally loaded piles and pile groups by assuming the soil as a homogeneous elastic continuum. In this analysis, the soil is assumed to be a homogeneous, isotropic, semi-infinite elastic material which is unaffected by presence of pile and also the soil at the back of the pile near the surface adheres to the pile (Poulos et al. 1980). In this model the pile is assumed to be a thin rectangular vertical strip divided into elements, and it is considered that each element is acted upon by uniform horizontal stresses (Fig. 4) which are related to the element displacements through the integral solution of Mindlin's problem. Finally, the soil pressures over each element are obtained by solving the differential equation of equilibrium of a beam element on a continuous soil with the Finite Difference Method (FDM). After the acquisition of the pressures, the displacements are found.



(A) (B)

FIG. 4 CONTINUUM MODEL FOR LATERALLY LOADED PILE STRESSES ACTING ON (A) PILE (B) SOIL ADJACENT TO PILE

As well Novak in 1974 presented an approximate continuum approach to account for soil-pile interaction, in which it is assumed that the homogeneous soil layer is composed of a set of independent horizontal layers of infinitesimal thickness, extending to infinity. As each plane is considered independent, this model may be viewed as a generalized Winkler model. The planes are homogeneous, isotropic, and linearly elastic, and considered to be in a plane strain state. The researcher presented the stiffness constants and

constants of equivalent viscous damping for single, vertical piles in the form of tables and charts in which he gave it for two different cases like a constant soil shear modulus and shear modulus varies with depth according to a quadratic parabola.

Elastic continuum approach was used by Madhav and Sarma (1982) to study the behaviour of overhang pile embedded in homogeneous soil mass subjected to both axial and lateral loads. The load displacement behaviour was found to be dependent on magnitude of axial load and also on pile and soil parameters (height of overhang, relative stiffness of pile and soil, undrained shear strength).

The Continuum model has the advantage that it is able to take into account the continuous nature of soil, the semi-infinite dimension of the half-space, and the boundary conditions along the unloaded ground surface. Although yielding of soil may be introduced by varying the soil elastic modulus, this approach does not permit to consider local yielding and layered soil. One of the biggest limitations of the method (in addition to computational complexities) is the difficulty in determining an appropriate soil modulus, K_h.

4) Finite Element Method

The finite element method is a numerical approach based on elastic continuum theory that can be used to model pile-soil-pile interaction by considering the soil as a three-dimensional, quasi-elastic continuum. Finite element techniques have been used to analyse complicated loading conditions in which the soil is modelled as a continuum.- Pile displacements and stresses are evaluated by solving the classic beam bending equation using one of the standard numerical methods such as Galerkin, Collocation, or Rayleigh-Ritz. Various types of elements are used to represent the different structural components. Interface elements are often used to model the soil-pile interface.- These elements provide for frictional behaviour when there is contact between pile and soil, and do not allow transmittal of forces across the interface when the pile is separated from the soil (Brown and Shie 1991).

Salient features of this powerful method include the ability to apply any combination of axial, torsion, and lateral loads; the capability of considering the nonlinear behaviour of structure and soil; and the potential to model pile-soil-pile-structure interactions. Time dependent results can be obtained and more intricate conditions such as battered piles, slopes, excavations, tie-backs, and construction sequencing can be modelled.- The method can be used with a variety of soil stress-strain relationships, and is suitable to analyze pile group behaviour, as described in next Section. The implementation of three-dimensional finite element analyses requires considerable engineering time to generate input and interpret results. For this reason, the finite element method has predominately been used for research on pile group behaviour, rarely for design.

Analytical Methods for Group Piles

Single pile analytical techniques are not sufficient in themselves to analyse piles within a closely spaced group because of pile-soil-pile interactions and shadowing effects. Numerous methods have been proposed over the last 40 years to evaluate the lateral resistance of piles within a closely spaced group. All those methods can be summarized and grouped under the following four headings

1) Closed form analytical approaches
2) Elastic Continuum Approach
3) Hybrid methods
4) Finite Element Method

1) Closed form analytical approach

Many of the methods in this category combine empirical modifying factors with single-pile analytical techniques. The oldest techniques simply involve the application of a group efficiency factor to the coefficient of sub grade reaction. Kim (1969) used this approach to model the soil and replaced the pile with an equivalent cantilever beam. Bogard and Matlock (1983) who utilized a group efficiency factor to soften the soil response and modeled the pile group as an equivalent large pile by means of a group efficiency factor concluded that the deflection of piles in a group is related to both the deflection of the piles acting individually and the deflection of the large equivalent pile. O'Neill (1983), Brown and Reese (1985) and Reese and Wang (1997) developed empirical analytical approach called the p-multiplier approach to account for pile group shadowing effects. The p-y curve is softened or weakened by multiplying the

soil resistance, p, by a reduction factor, f_m. This method is combined with a structural matrix analysis package in the computer program GROUP. Novak and Janes (1989) developed closed form expressions to evaluate group stiffness and damping. These expressions can be applied to estimate group response under small displacements, as a result of static and dynamic lateral loads. Ashour et al. (1996) developed an analytical approach (incorporated into the computer program SWSG) known as the strain wedge model to evaluate the response of piles and pile groups. This model relates 1D beam on elastic foundation analysis to 3D soil pile interaction response and is based on the deformation of soil within a plastic wedge in front of the pile. Plane stress conditions are assumed within the wedge and group effects are quantified by considering the overlap of passive wedges and accompanying strains (Mokwa 1999).

2) Elastic Continuum Approach

Methods that fall into this category model the soil around the piles as a three-dimensional, linearly elastic continuum. Mindlin's equations for a homogenous, isotropic, semi-infinite solid are used to calculate deformations. This is similar to the single pile approach except that elastic interaction factors are incorporated into the analyses. These factors are used to address the added displacements and rotations of a pile within a group caused by movements of adjacent piles. Poulos (1971 a, b) modeled pile-soil interactions using elastic continuum methods that consider the soil to act as a 3-D, linearly elastic, homogeneous, isotropic, semi-infinite medium in which Mindlin's equations are used. Poulos and Davis (1980) present the interaction factors that account for additional displacements (α_p) and rotations (α_θ) in chart form for various conditions. The displacement and rotations of any pile in the group is obtained using the principle of superposition, which implies that the increase in displacement of a pile as all the surrounding piles can be calculated by summing the increases in displacement due to each pile in turn using interaction factors. Ochoa and O'Neill (1989) presented a method to analyze pile groups using elasticity theory with experimentally determined interaction factors. Iyer and Sam (1991) developed a method to estimate the stresses in a 3-pile cap using 3-D elasticity solutions expressed in terms of the Galerkin vector and double Fourier series. The cap was modeled as a thick rectangular block with patch loadings on the top and bottom faces. They concluded that this method of structural analysis was more accurate than the truss analogy and beam methods.

3) Hybrid Methods

These methods are called hybrid because they combine the nonlinear p-y method with the elastic continuum approach. p-y curves are used to model the component of soil deflection that occurs close to individual piles (shadow effect) and elastic continuum methods are used to approximate the effects of pile-soil interaction in the less highly stressed soil further from the piles. Focht and Koch (1973) developed the original hybrid procedure that uses p-y curves to model pile-soil interaction and Mindlin's equations with elasticity based α -factors to approximate the group effects of pile-soil-pile-interaction and presents a procedure for including interaction effects of closely spaced piles by applying y-multipliers to single pile p-y curves. Reese et al. (1984) modified the Focht-Koch approach by using solutions from p-y analyses to estimate elastic deflections where load-deflection behavior is linear. O'Neill et al. (1977) modified the Focht-Koch approach by adjusting unit-load transfer curves individually to account for stresses induced by adjacent piles. Additional hybrid approaches include Garassino's (1994) iterative elasticity method and Ooi and Duncan's (1994) group amplification procedure. Ooi and Duncan performed a parametric study of pile group response using the Focht-Koch procedure. A method is developed to estimate the increased deflections and bending moments in laterally loaded piles and drilled shafts caused by group interaction effects. Design charts and equations were developed to determine deflections and bending moments of closely spaced piles.

4) Finite Element Method

The analysis of group piles using this method is carried out in the same way as described in single pile analysis. Desai et al. (1980) employing a much more rigorous approach to calculate the soil modulus in their two-dimensional approach calculated nonlinear p-y curves using the tangent modulus, E, obtained from a modified form of the Ramberg-Osgood model. Randolph (1981) performed parametric studies using finite element methods and Poulos's elasticity approach to

develop algebraic equations to estimate the lateral response of single piles. The analysis has been extended to consider pile groups by developing expressions for interaction factors for closely spaced piles. The solutions are simpler than previous continuum methods because they are independent of the embedment length of the pile. Randolph reported that only in rare cases will the length of the pile be a factor. Tamura et al. (1982) performed 3-D finite element analyses using the hyperbolic model to represent the stress-stain characteristics of the soil. Parametric studies were performed to evaluate group effects related to pile spacing and quantity of piles. It has been concluded that pile group effects increase as the number of piles in the direction of load application increases and as pile spacing decreases. It was observed that the inner piles took a greater portion of load and had larger group effects than the outer piles. Najjar and Zaman (1988) performed nonlinear 3-D finite element analyses to investigate the effects of loading sequence and soil nonlinearity on the deformation behavior of a pile group. The behavior of the pile and cap was assumed linear. A nonlinear constitutive model was used for the soil. It has been concluded that loading sequence and soil nonlinearity can significantly affect the lateral and axial response of pile groups.

Brown and Shie (1991) performed a detailed parametric study using a 3-D finite element model to evaluate the combined effects of superposition of elastic strains and shadowing. Two constitutive models for soil were used; an elastic-plastic constant yield strength (Von Mises envelope) for undrained loading of saturated clay, and an extended Drucker-Prager model with a nonassociated flow rule was used for sand.- Recommendations were developed to modify p-y curves (as a function of pile spacing) using p- and y-multipliers. It has been observed that these multipliers vary as a function of depth and soil type. Rao and Ramakrishna (1995) analyzed 2-pile and 3-pile groups using 2 d finite element method with pile spacing varying from 3D to 8D and with cap thickness varying from 0.12 in to 0.60 in. (The pile caps were not in contact with the soil). It has been concluded that the lateral resistance of a pile group depends on not only the spacing between piles but also on the thickness of the pile cap. The pile cap deforms as a flexible body when its thickness is small and deformed as a rigid body at larger thickness. Rao et al. (1996) Performed simplified plain strain finite element analyses to evaluate group efficiencies for various pile spacing's and geometric arrangements. The calculated results were compared with those obtained from 1g model tests.

Review and Discussions

The presented review in this paper shows that the research on "Soil structure interaction analysis of framed structures supported on pile foundation" has evolved in 1970's in which the analysis was carried out in single step to assess the effect of soil structure interaction on the response of structure in terms of changes in member forces and settlements but the stiffness of pile cap was excluded from consideration. It has been observed that pile caps provide considerable resistance to lateral loads on deep foundation systems. The missing of this resistance has resulted in excessive estimates of pile group deflections and bending moments under load, and underestimates the foundation stiffness (Mokwa 1999).

After that hardly any work was reported on the same till 2000 when` the SSI analysis was carried out using successive incremental solution scheme to study the interaction effect of a two storied single bay structure supported on pile foundation. But in this analysis fixed boundary condition is assumed and also damping terms in dynamic equilibrium equation are neglected. It has been observed that under cyclic loading the damping is increased in soils as number of cycles of load increases and the missing of this effect either in linear and nonlinear analysis will results in response which is totally different from actual response.

Later in 2002 Yingcai studied dynamic analysis of tall buildings using DYNAN and from the results it has been concluded that the seismic behavior of a tall building supported on a pile foundation is different from that on a shallow foundation or a rigid base. The theoretical prediction for tall buildings fixed on a rigid base without soil-structure interaction does not represent the real seismic response, since the stiffness is overestimated and the damping is underestimated

Also in 2003 Lu et al., studied the influence of parameters such as soil property, rigidity of structure, buried depth on SSI system by considering a 12 storey frame structure supported on pile-raft foundation using ANSYS. In this study he did a dynamic analysis

with a linear soil model, but under strong earthquake excitation, structure and soil adjacent to foundation work in plastic range, the neglection of this effect does not represent the real seismic response of structure.

Recently, from 2008 the SSI analysis of two bay single storey structure was carried out using substructure approach. In this analysis the soil was modelled as linearly elastic independent springs and the response of structure was calculated by giving lateral load at the top of the frame (Chore 2010). More recently in 2012 the SSI analysis of a four bay twelve story RCC frame was done by using discrete finite lement method (NISA). However, in this soil is modeled by using discrete springs and also a linear static analysis is done by giving static equivalent of earthquake load (Deepa et al., 2012). It has been observed that modelling the soil as continuum will offer more passive resistance thus leading to larger soil stiffness. So the neglection of this continuous nature of soil will give results far from reality.

Based on the literature pertaining to SSI analysis of framed structure supported on pile foundations it has been observed that most of studies reported till now has considered the marginal effect of soil structure interaction on a one and two bay single storied and two storied framed structures. As such, there is a need to evaluate the effect of SSI on the response of high-rise structure.

In addition, the analysis were carried out as static analysis by the application of lateral load at the top of the frame, so there is a need to understand the dynamic response of super structure by considering complex behaviour of framed structure supported on pile foundations subjected to dynamic forces.

Further, soil pile structure interaction analysis of a building with infill walls has not been studied. Under lateral loading, infill wall imparts considerable lateral stiffness to the structure, hence the effect of the same must be incorporated in the dynamic analysis.

Soil pile structure interaction analysis has not been studied by modelling the separation between pile and soil (Interface modelling) as well.

Conclusions

The review of current state-of-the art of the modeling of frame structures supported on pile foundations leads to the following broad conclusions.

1. To accurately estimate the response of structure, the effect of soil structure interaction is needed to be considered under the influence of both static and dynamic loading.

2. Finite element method has found to be very useful method to study the soil structure interaction effect with rigor. In fact, the technique becomes useful to incorporate the effect of material nonlinearity, nonhomogeneity and interface modeling of soil and foundation.

3. Although some attempts have been made to study the interaction effect of framed structures supported on pile foundations, still a detailed analysis considering the nonlinear soil model and gap separation between pile and soil has not been addressed.

4. From the study of Chore et al. 2010 it has been observed that in spite of acquisition of accurate results for representing soil as Winkler spring, the effect of passive resistance of soil (which comes from full scale soil pile model) also plays a major role in the response of system.

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